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THE MAGNETIC FIELD INVESTIGATION ON CLUSTER

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ABSTRACT

The magnetic field investigation (FGM) is designed to provide inter-calibrated measurements of the magnetic field vector **B** at the four Cluster spacecraft. The objective of this investigation, like that of the mission as a whole, is the study of small scale plasma structures and processes in the Earth's environment. The instrumentation is identical on the four spacecraft: it consists of two tri-axial fluxgate sensors and of a failure tolerant Data Processing Unit. The combined analysis of the four-spacecraft data will yield such parameters as the current density vector, wave vectors and the geometry and structure of discontinuities. This paper outlines both the instrumentation to be used and the proposed data analysis techniques.

Keywords: magnetosphere, magnetic field, space plasma, fluxgate magnetometer

1. INTRODUCTION

Cluster is a new type of magnetospheric mission, providing an opportunity to determine, through the use of the four-spacecraft configuration, the three dimensional, time dependent characteristics of small scale structures in the near-Earth space plasma both in the magnetosphere and in the nearby interplanetary medium.

When magnetised plasmas from different sources interact, the high electrical conductivity of the plasmas prevent them from mixing readily. Instead, a thin boundary current sheet is formed between them. The interactions which then occur to transfer mass, momentum and energy between the two plasmas involve small scale phenomena operating in the boundary, such as localised, transient *reconnection* (flux transfer events) or turbulent diffusion. Additionally, at super-magnetosonic relative flow speeds, a shock is formed upstream of the boundary, again involving processes on small spatial scales.

Phenomena such as these are ubiquitous in all cosmic plasmas, but can only be studied in situ in solar system plasmas. The closest available space plasmas for detailed study are to be found in the Earth's magnetosphere and in the region of its interaction with the solar wind. The orbit of Cluster has been chosen to sample most of the key features of this system. The regions which will be studied by Cluster are the dayside magnetospheric boundary, both at mid-latitudes and in the cusp where processes associated with magnetic reconnection and turbulence are believed to occur, the near-Earth magnetospheric tail on the nightside which undergoes periodic large-scale magnetic reconfigurations during substorms, and the upstream solar wind, bow shock and magnetosheath.

In the context of the overall mission aims, it is obvious that an accurate determination of the magnetic field is basic to any plasma physics investigation. In a magnetised plasma, the magnetic field largely orders the plasma populations and strongly influences the propagation of waves. Thus not only is the magnetic field investigation to be regarded as a research instrument in its own right, but it also provides information which is essential for interpreting data obtained by other instruments.

In the next section of this paper we present considerations concerning the analysis of the four-spacecraft magnetic field data. The novelty of Cluster is that it provides the opportunity to derive three dimensional, time-dependent parameters characterising the plasma, such as current density vectors, wave vectors and vector normals of discontinuities and boundaries. The applicability and limitations of the data analysis techniques are dependent not only on the physics and scale sizes of phenomena along the orbit of Cluster, but also on the accuracy, in space and time, with which the four-spacecraft configuration is defined, the inter-calibration of the magnetometers, and the success of the magnetic cleanliness programme.

A detailed description of the instrumentation being developed for Cluster is given in Section 3. Despite a number of uncertainties concerning the implementation of the instrument (acceptable at this stage of the development programme), its main characteristics and performance parameters have been fully defined. The organisation and tasks of the international investigator team are given in Section 4.

2. FOUR-SPACECRAFT DATA ANALYSIS TECHNIQUES

2.1 The Cluster magnetic field data set

The data required by this investigation consists not only of the output of the instrument, but also of information on the orbit, attitude and time of each one of the four spacecraft. We define the primary data set as follows:

- the simultaneous measurement of the magnetic field vector at four locations in space,
- the three vectors giving the relative locations of three spacecraft with respect to the fourth, taken as the reference, and
- the vector giving the location of the reference spacecraft in an Earth-related inertial coordinate sytem.

All eight vectors are determined as a function of time and in coordinate systems which must be related to each other in a known way.

In the following subsections we describe three techniques, using this data set, which will be routinely implemented in the data analysis programme. All three imply making assumptions about the processes being investigated, but all three are susceptible to powerful validity checking techniques.

The logic implicit in these techniques can be extended to the use of more general model testing methods, as already introduced in other branches of geophysics. Briefly stated, quantitative tests of models, theoretical or semi-empirical, can be carried out by calculating cross-correlation (or overlap) integrals between models and the data set. The development of such analysis techniques is an important pre-launch activity, involving the development of physical models and quantitative test procedures, as well as the preparation of basic processing for intercalibration of instruments in flight.

2.2 Determination of the current density vector

The first and most publicised use of the four spacecraft magnetic field data is the determination of the current density vector by applying the integral form of Ampere's law to the faces and edges of the tetrahedron formed by the four spacecraft, using the vectors specifying their separations and the vector differences of the magnetic field measured by the four magnetometers. This technique, which we name the "curlometer" because it provides a measure of **curl B**, is equivalent to a measurement of the average current density vector, as illustrated schematically in Figure 1.

The method is limited to the case when the field varies uniformly within the tetrahedron, or equivalently, when the current distribution is uniform on the separation scale of the spacecraft. Current distributions are expected to have scale sizes about 100 km, smaller than the Cluster spacecraft separations, at several locations along the orbit, such as in the magnetopause, the plasma sheet boundary, shocks etc. A good estimate of the quality can be obtained by evaluating the residual value of div **B**, or the total flux of the field through the faces of the tetrahedron. This value should be small (when compared to the magnitude of **curl B**), otherwise the current density estimates are unsafe to use without further consideration, if at all.

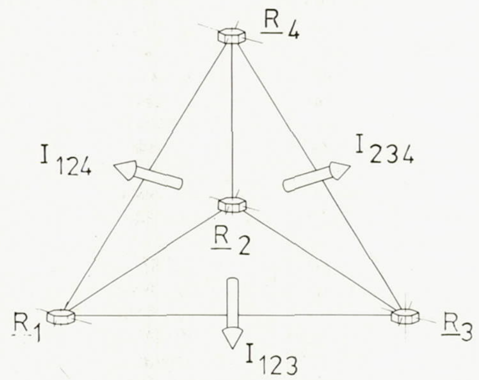

Figure 1. The Cluster tetrahedron, indicating the currents which can be calculated using Ampere's law.

The estimate of the current density is also very sensitive to the accuracy with which the separation vectors are known; and, because of the use of vector differences of **B** between magnetometers, to the intercalibration of the instruments, the knowledge of their orientation and alignment, and the residual magnetic field of the spacecraft at the location of the sensors. All these potential error sources interact strongly in the estimate of the current density. An extensive modelling programme of the potential error sources has been

initiated to assist with the scientific data analysis. A preliminary result is that for an estimate of the current density vector accurate to 5%, vector separations must be known with an error of 1%.

2.3 The wave telescope technique

The characterisation of waves in the magnetosphere, magnetosheath and nearby interplanetary space is an important objective for Cluster. If the combined analysis of the magnetic field data from the four spacecraft is done in the the wave number vs. frequency domain, rather than in space and time, information on wave vectors can be derived, assuming that the observed waves can be analysed in terms of monochromatic plane waves with wavelengths comparable or larger than the Cluster separation distances.

Although this assumption is restrictive and is not likely to be valid generally, there are a number of ways in which the applicability of the technique can be tested. Waves can be characterised by this technique if they are coherent at the location of the four spacecraft. The coherence length of the signals is likely to be only a few times the wavelength unless the waves are very monochrome, so that for wavelengths much shorter than the spacecraft separation, signals will fail the coherence test. This and other physical constraints, such as the divergence-free nature of the magnetic field, will assist in establishing the validity of results derived by this technique.

2.4 Discontinuity analysis

The determination of the geometry and structure of discontinuities, boundaries and shock waves is one of the major objectives of Cluster. The simplest assumption is that discontinuities are planar on the scale of the inter-spacecraft distance. Calculation of the normals at the four sites, using minimum variance algorithms, is a powerful test of the assumption, together with the timing of the discontinuity by the four spacecraft.

A quantitative proof of planarity, or a measure of the departure from planarity will be the starting point for systematic studies on the structure of discontinuities and interface phenomena.

3. INSTRUMENT DESCRIPTION

Identical instruments are foreseen for all four Cluster spacecraft. Each instrument consists of two boom-mounted triaxial fluxgate sensors and an electronics unit in the spacecraft containing the drive and sense electronics of the sensors, signal multiplexers and analogue-to-digital converters, a dual-processor Data Processing Unit, and a dual DC-DC power converter. The block diagram of the instrument is shown in Figure 2.

Magnetometers have become classical instruments on all particles-and-fields missions. For several years now, magnetometers have outperformed the mission requirements in terms of sensitivity, resolution and noise level. The key differences in instrument performance from mission to mission have come from the available telemetry rates, the amount of onboard processing and the level and stability of the background magnetic field due to the spacecraft.

In the case of Cluster, the magnetometer sensors and their electronics have been inherited from previous missions, such as Giotto and AMPTE(CCE). However, the scientific requirements (data analysis in terms of vector differences between spacecraft) now call for higher resolution, hence the need for 14-bit analogue-to-digital conversion. The use of microprocessors enable a more flexible approach to onboard processing, used for filtering, event recognition etc. Furthermore, the design aim is to eliminate single point failure modes, in other terms, to make the instrument failure tolerant.

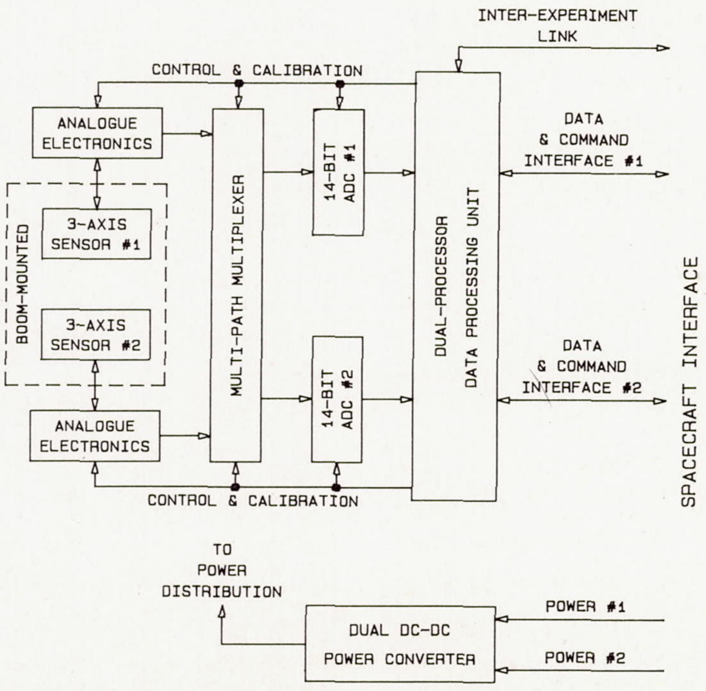

Figure 2. Block diagram of the Cluster magnetometer.

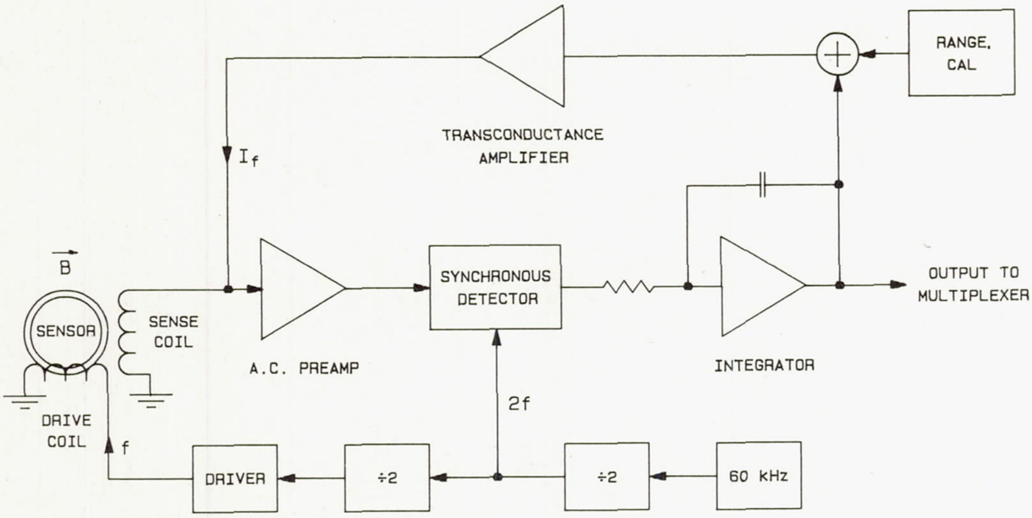

Figure 3. Block diagram of a single axis fluxgate magnetometer.

3.1 The fluxgate magnetometers

Fluxgate sensors have been proved rugged and very reliable in space use. Their performance fully satisfies the scientific requirements of the mission. The schematic block diagram of a single axis sensor is shown in Figure 3.

A fluxgate magnetometer consists of three elements: a sensor, the drive electronics, and the sense electronics. The sensor to be used for Cluster has a toroidal magnetic core, with a toroidal primary winding, carrying the drive signal, in this instance a differentiated square wave of about 15 kHz, driving the core deep into saturation twice per cycle. The secondary winding is placed on a rectangular coil former around the core; the axis of the secondary or sense winding is the axis of the sensor.

The signal out of the sensor at the second harmonic frequency of the drive waveform is proportional to the component of the ambient field along the sensor axis. This signal is first amplified then detected synchronously with a phase sensitive detector, integrated, and fed back in the form of current (hence the use of a voltage-to-current converter, or transconductance amplifier) to the sense winding to make the sensor operate close to its null point. The drive waveform generator also provides the second harmonic phase reference used in the synchronous detector.

Three sensors, arranged in an orthogonal triad, constitute each of the two sensor assemblies to be mounted on the spacecraft boom. The two sets of sensors for each spacecraft are required partly for redundancy, and partly for monitoring the in-flight background fields of the spacecraft. The sensors are linked by the boom cable harness to their respective drive and sense units in the instrument electronics box in the spacecraft.

The magnetometers are eight range instruments, providing a bipolar full scale output voltage for field values from +/- 4 nT to +/- 65,536 nT, each range being four times the preceeding range. Range switching will be controlled automatically by the DPU. It is planned to use only four of the ranges, as shown in Table 1.

TABLE 1

Range	Resolution
+/- 256 nT	+/- 0.015 nT
+/- 1024 nT	+/- 0.061 nT
+/- 8192 nT	+/- 0.5 nT
+/- 65536 nT	+/- 4 nT

The 65,536 nT range is reserved for ground testing. The resolution shown in Table 1 results from the use of a 14-bit ADC.

In view of the expected low temperature (-100 ^{o}C) during eclipses, a 0.25 W heater is incorporated in the sensors, powered by a 40 kHz inverter in the electronics unit, using a dedicated power supply.

3.2 Analogue-to-digital conversion

The two sensors provide three analogue voltages each, corresponding to the components of the magnetic field vector measured by the sensors. The signals from both sensors are fed in parallel to two analogue multiplexers, followed by two 14-bit analogue-to-digital converters (ADC).

In routine operation only one of the paths will be used, controlled by the DPU, normally on ground command. (It is foreseen that automatic switching will also be incorporated, for use in failure recovery and during the in-flight calibration test sequence.)

The ADCs used are 16-bit successive approximation types, short cycled to 14 bits, with timing and sequencing signals generated by the DPU. The conversion time for each vector is about 0.2 ms.

3.3 The Data Processing Unit (DPU)

The functions of the DPU are:

- Control and sequencing of the digitisation of the analogue voltages representing the magnetic field components measured by the sensors. The nominal

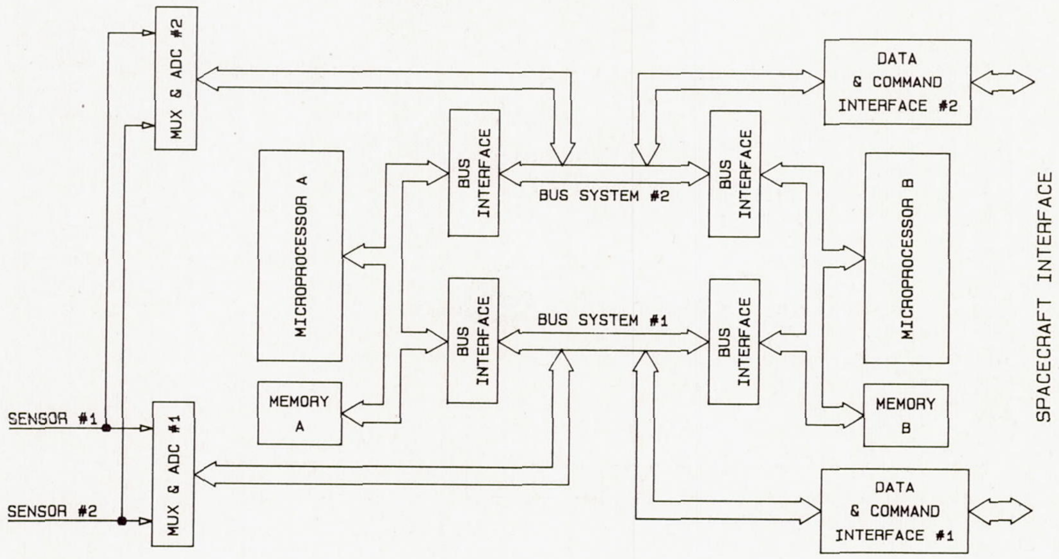

Figure 4. Block diagram of the Data Processing Unit.

internal sampling rate is 100 vectors/s, although this figure is yet to be confirmed when the final telemetry rate and intermediary digital filtering algorithms (see below) are confirmed. Sampling is synchronous with the spacecraft clock, not with the spin.

- Range control of the magnetometers. Upranging is implemented if any of the three components reaches a value in an upper guard band (defined as the upper 10% of the range). The instrument will be put into the lower range if all three components of the vector remain in the lower guard band (defined as the lower 10% of the range) for a complete spin of the spacecraft. Automatic ranging can be overridden by ground command. The range control is given to each magnetometer in the form of a three-bit command word.

- Processing of magnetic field data for telemetry transmission. The primary DC to 50 Hz bandwidth is aimed to study the neighbourhood of shocks, where there is enough wave power in the upper end of this frequency range. For routine telemetry transmission, a rate of 1000 bps has been allocated, enough to transmit about 20 vectors/s. The DPU will process the full bandwidth digitised data stream, using digital filtering to tailor the bandwidth of the output to the transmitted data rate. The current plan is that in routine operations the outboard magnetometer will generate 16 vectors/s, while the transmitted rate from the inboard sensor will be 4 vectors/s. Other options can also be implemented, for example a mode in which the two sensors generate the same data rate.

The deletion of an event triggered burst memory mode in the spacecraft can be to some extent mitigated by generating standard deviation data and by computing band pass filtered values of the field magnitude. The use of such data is to flag events when a high rate of change is observed, or there is significant power in upper part of the frequency band of the instrument. The detailed processing requirements for this purpose will need to be reviewed when higher priority tasks for the DPU are better defined.

- Telecommand and telemetry interfaces with the spacecraft data and command subsystem. As yet these are largely undefined, although a crude form of packetised telemetry is being envisaged for the mission. The DPU will assemble the instrument data packets for transmission to the telemetry system. Telecommands will be decoded and implemented by the DPU.

- Instrument health monitoring. The DPU will collect and prepare for transmission internal digital and analogue housekeeping channels. Furthermore, there will be at least a limited ability built into the DPU to monitor the health of specific functions so that it can perform some self-checking and failure reconfiguration. These functions can be modified or overridden by ground command.

- Control and sequencing of in-flight tests. The instrument has built-in test sequences both for the digital and the analogue/sensor parts. These test sequences are initited by ground command, but controlled by the DPU.

- Provision of magnetic field data to most other instruments. This function is described separately in Sub-section 3.4.

The key to the design of the DPU is the selection of the microprocessor type and its related devices. The block diagram of the DPU in Figure 4 is based on the 80C86 family of microprocessor and peripheral devices which combine low power, high performance and high tolerance to the radiation environment of Cluster. However, their availability has not been assured, so that alternatives (transputers, MD281) are being evaluated.

However, the architecture shown in Figure 4 is a good guide to the design goals of the DPU. A failure tolerant DPU needs a minimum of two processors, each having access to all the functions and interfaces which need to be incorporated. This design uses two bus systems, including data, address and control buses, isolated by protected bus interface units. Input and output functions, such as the ADCs and spacecraft interface units are

memory mapped through the bus system, but need to be duplicated to avoid single point or function failure modes. Each microprocessor has its own programme and scratch memory. The software is held mostly in ROMs in order to minimise the amount of code that needs uplinking every time the instrument is switched on. The design of the flight software will be highly modular to provide sufficient flexibility but needing only minimal reprogramming.

The two microprocessors will normally perform different functions: while one will handle the data acquisition process, including the digital filtering, the other will handle the interface tasks, both with the spacecraft and with other instruments. In case of failure of one of the processor units, the other is able to take over some of the vital tasks, so that the instrument can maintain a basic operational level.

3.4 The inter-experiment link.

Other instruments on Cluster, such as the plasma detectors and the electron gun require the magnetic field data in real time for use in the onboard acquisition and processing of their own data. The interface and the data to be transmitted have not been finalised at this stage. It has been proposed to provide the raw data, as telemetered for the magnetometer itself, but in a continuous data stream, rather than in the form of the assembled packets.

The basic data format which has been proposed consists of contiguous, synchronous data words of 64 bits, transmitted 16 times per second. Each data word would contain a start bit, the three components of the magnetic field vector, with a resolution of 12 bits, and 3 bits of range information. The rest of the word is filled with zeros. No protocol is envisaged, the data would be simply loaded into a user experiment's register at 62.5 ms intervals. The shift clock will be continuous at 1024 Hz. The data are in spinning spacecraft coordinates (no despinning is planned on board) and uncorrected for offsets. However, information on offsets and gains needed for interpreting the data will be made available to users of the link.

4. IMPLEMENTATION PLANS

The definition status of the instrumentation is quite advanced so that most major characteristics and interfaces are known. The detailed design of most subsystems has been initiated. There is of course a great deal of previous experience in most areas, and beyond the customary difficulties caused by mass, power and financial constraints, the implementation of the instrument is not regarded as involving high risks.

The mass of the instrument has been set at 2.8 kg, including the two sensors, the electronics box and the boom harness connecting the sensors to the electronics. The primary power for the instrument is 2.7 W.

A key issue for the investigation is the magnetic cleanliness of the spacecraft. Past experience has shown that it is possible to build magnetically clean spacecraft, but not without a significant effort on the part of all participants in the mission. For the Cluster programme it has been decided to implement a partnership, through the Electromagnetic Cleanliness Board, between the experimenters, the ESA Programme Office and the prime contractor to be selected, to set up an appropriate test programme and to ensure the required discipline needed to meet the design goal of 0.25 nT background field at the sensor location on the boom. The stability of the background must also be better than 0.1 nT in 100 seconds.

For the implementation of the instrument and the processing and analysis of the data, the Investigator Team has agreed to share the tasks as follows:

Imperial College: Overall system design and leadership of the investigation; design and construction of the DPU, power supply, electronics box, Electrical Ground Support Equipment; magnetic cleanliness programme; environmental testing; data processing; flight operations.

Technische Universitat Braunschweig: Instrument calibration programme; participation in the DPU design and construction; magnetic cleanliness programme.

Koln Universitat: Data reduction and processing; participation in the magnetic cleanliness and instrument calibration programmes.

Institut fur Weltraumforschung, Graz: Design and construction of the analogue multiplexers and A-D converters; part of the flight software; magnetic cleanliness programme.

NASA/GSFC: Provision of the magnetometer sensors, their analogue electronics and the boom cables.

UCLA: Data reduction and processing, software for intercalibration in flight.

Dansk Rumforkningsinstitut: Support for the magnetic cleanliness and instrument calibration programmes.

CRPE/CNET: Magnetic cleanliness support; liaison with the Cluster wave consortium.

JPL: Data simulation/modelling.

This list identifies only the major tasks of each group. All investigators are expected to play a full and equal part in the scientific analysis of the data.

The Investigator Team is conscious of the unprecedented opportunity for major advances in understanding magnetospheric processes offered by the Cluster mission. It is ready to make all the necessary effort to make the mission a success.

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